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Effects of California's Climate Policy in Facilitating CCUS

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Abstract

California is at the forefront of addressing the challenges involved in redesigning its energy infrastructure to meet 2050 GHG reduction goals, but CCUS commercialization lags in California as it does elsewhere. It is unclear why this is the case given the state's forefront position in aggressive climate change policy. The intent of this paper is to examine the factors that may explain why CCUS has not advanced as rapidly as other GHG emissions mitigation technologies in California and identify ways by which CCUS commercialization may be advanced in the context of California's future energy infrastructure.

CCUS has application to reduce GHG emissions from the power, industrial and transportation sectors in the state. Efficiency, use of renewable energy or nuclear generation to replace fossil fuels, use of lower or no-net-carbon feedstocks (such as biomass), and use of CCUS on fossil fuel generation are the main options, but California has fewer options for making the deep cuts in CO_2 emissions within the electricity sector to meet 2050 goals. California is already the most efficient of all 50 states as measured by electricity use per capita, and, while further efficiency measures can reduce per capita consumption, increasing population is still driving electricity demand upwards. A 1976 law prevents building any new nuclear plants until a federal high-level nuclear waste repository is approved. Most all in-state electricity generation already comes from natural gas; although California does plan to eliminate electricity imports from out-of-state coal-fired generation. Thus, the two options with greatest potential to reduce in-state power sector CO_2 emissions are replacing fossil with renewable generation or employing CCUS on natural gas power plants. Although some scenarios call on California to transition its electricity sector to 100 percent renewables, it is unclear how practical this approach is given the intermittency of renewable generation, mismatches between peak generation times and demand times, and the rate of progress in developing technologies for large-scale power storage.

Vehicles must be electrified or move to biofuels or zero-carbon fuels in order to decarbonize the transportation sector. These options transfer the carbon footprint of transportation to other sectors: the power sector in the case of electric vehicles and the industrial and agricultural sectors in the case of biofuels or zero-carbon fuels. Thus, the underlying presumption to achieve overall carbon reductions is that the electricity used by vehicles does not raise the carbon emissions of the power sector: biofuel feedstock growth,

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harvest, and processing uses low carbon energy or production of fuels from fossil feedstocks employs CCUS. This results in future transportation sector energy derived solely from renewables, biomass, or fossil fuel point sources utilizing CCUS.
In the industrial sector, the largest contributors to GHG emissions are transportation fuel refineries and cement plants. Emissions from refineries come from on-site power generation and hydrogen plants; while fuel mixes can be changed to reduce the GHG emissions from processing and renewable sources can be used to generate power, total decarbonization requires use of CCUS. Similarly, for cement plants, power generation may use carbon-free feedstocks instead of fossil fuels, but CO_2 emissions associated with the manufacture of cement products must be dealt with through CCUS. Of course, another option for these facilities is the purchase of offsets to create a zero-emissions plant.
In spite of the conclusion that CCUS is vital to decarbonization of three of the state's key economic sectors, incorporating CCUS technology into California's energy future has significant challenges. A diverse set of questions must be addressed before state planners, policymakers, and regulators will be able to justify pursuing CCUS as a part of the solution to meet 2050 goals:

- In what sector applications does CCUS have the most potential to assist the state in reducing its CO2 emissions?
- Do policies to facilitate CCUS enable continued use of fossil fuels even where there may be other viable options for energy generation?
- Are CCUS technologies, specifically subsurface storage elements, safe and effective over the long term?
- How can California agencies and lawmakers assure that CCUS projects are appropriately permitted, regulated, monitored, and verified?
- Can the state's industrial and energy infrastructure accommodate the changes necessary to integrate CCUS?
- In state planning for future energy infrastructure, should CCUS be included as a component? What is the risk in not doing so?
- If CCUS is to be relied on to reduce significant fractions of California's future emissions, at what rate should CCUS projects be coming on line, and what pathways to commercialization can accommodate this rate?

CCUS projects worldwide and analog projects provide some data and experience to answer these questions. Worldwide experience, for example, supports the assertion that CO_2 can be stored safely in the subsurface; these projects have tested a number of tools, including monitoring technologies, simulations, well completion methods and well and cap rock integrity testing to give regulators confidence that risks are measureable and verifiable. For California, areas of particular concern are assuring safety of groundwater resources from contamination and seismic hazards. California has plentiful geologic storage resource to accommodate captured emissions, according to studies by WESTCARB and the California Geological Survey.
Infrastructure requirements include capture facilities at CO_2 emission sources, pipelines, and injection and monitoring wells at storage sites. It is a policy decision as to whether these costs should be passed on to consumers or taxpayers. California will require substantial investment in pipeline infrastructure in order for CCUS to become widespread. Because a readily available supply of low cost CO2 would benefit California's oil industry, that industry and federal subsidies for oil production may be sources of capital for pipeline development. California's CCUS project developers may be able to repurpose or co-utilize some existing infrastructure at California's numerous oil and natural gas fields if storage is done in conjunction with CO2-EOR or by conversion of depleted reservoirs to storage sites. Storage in saline formations will require new infrastructure and development to assure safe and effective long term storage.
Rates of CCUS technology adoption must be sufficient to create a declining trend in GHG emissions with the right slope to intersect 80 MT or less total emissions by 2050. It is an oversimplification to assume that technology adoptions between now and 2050 will result in a linear reduction of emissions with time, but it serves to give a first-order approximation of the size of the task. With every year of delay in implementation of GHG reduction technologies, the slope becomes steeper. If the 2020 cap on new emissions is maintained after 2020, about 10 Mt per year must still be removed every year to reach the 2050 goal. This is equivalent to removing several of California's largest point sources from the emissions inventory every year.

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Keywords: carbon capture, utilization, and storage; California; energy policy; climate policy

1. Introduction

California is at the forefront of addressing the challenges involved in redesigning its energy infrastructure and addressing GHG emissions reductions to meet goals consistent with Intergovernmental Panel on Climate Change (IPCC) recommendations. Carbon capture, utilization and storage (CCUS) has potential applications to electricity, transportation and industrial economic sectors in the state. Analyses demonstrate that CCUS deployed on a variety of emissions sources, including carbon-neutral fuels, is an important part of the portfolio of options the state needs to meet its goals. Many state agencies have recognized the potential role that CCUS can play. Yet, in California, as in the rest of the world, CCUS commercialization lags behind other technologies that address GHG emissions. This situation is somewhat puzzling given the state's forefront position in aggressive climate change policy.

There is no doubt that incorporating CCUS technology into California's energy future has significant challenges. From a technical standpoint, the component technologies are mature and can be readily deployed at commercial-scale; however, CCUS technology as an integrated system is still in the development stage. The public and private investment in CCUS infrastructure must be substantial to commercialize the technology; and its acceptance would substantially change future directions for energy infrastructure. Thus, state policymakers must feel assured that choosing the CCUS path is both necessary to meet climate change goals and appropriate to the state's other needs, such as resource protection and economic equity and sustainability. This report seeks to answer a diverse set of questions to assist state planners, policymakers, and regulators in assessing why and how to include CCUS:

- In what sectors does CCUS have the most potential to assist the state in reducing its CO2 emissions?
- Do policies to facilitate CCUS enable continued use of fossil fuels even where there may be other viable options for energy generation?
- Are CCUS technologies, specifically subsurface storage elements, safe and effective over the long term?
- How can California agencies and lawmakers assure that CCUS projects are appropriately permitted, regulated, monitored, and verified?
- Can the state's industrial and energy infrastructure accommodate the changes necessary to integrate CCUS?
- In state planning for future energy infrastructure, should CCUS be included as a component? What is the risk in not doing so?
- If CCUS is to be relied on to reduce significant fractions of California's future emissions, at what rate should CCUS projects be coming on line, and what pathways to commercialization can accommodate this rate?

While the answers to some of these questions are unknown, insights can be gained from studying the experiences of other countries or states where CCUS has been analyzed or implemented to a larger extent than in California to date, by examining the technical data available from CCUS projects around the world, and by analyzing the results of many California-specific studies of CCUS and future energy infrastructure.

Nomenclature

ARB	California Air Resources Board
CCUS	Carbon capture, utilization and storage
EPS	Emission Performance Standard
GHG	Greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LBNL	Lawrence Berkeley National Laboratory
LCFS	Low-carbon fuel standard
NGCC	Natural gas combined-cycle

2. Energy Usage by Sector

The majority of California's energy use is in the electricity and transportation sectors, and these sectors also account for the majority of California's carbon emissions. As the transportation sector shifts to low-carbon fuels and electrification, the electricity sector may account for a relatively larger fraction.

The Energy Information Administration shows California as the second largest consumer of electricity in the United States, ranking below Texas. In 2010, California used about 273,000 GWh (1), nearly 7 percent of the national total of about 3,750,000 GWh; however, on a per capita basis, California ranks as the most energy-efficient of all 50 states, consuming 6,721kWh/person compared to a high in Wyoming of 27,457 kWh/person (2). Since the early 1970s, aggressive energy efficiency measures in California have maintained per capita electricity consumption at nearly constant levels, but population growth has resulted in overall increased electricity demand at a rate on the order of about a percent per year since 1990 (1).

Forecasts of electricity demand predict growth rates will be of the same order through 2022, resulting in electricity demand ranging from 309,000-334,000 GWh in 2022 (1). If these values are projected out for another three decades, electricity demand estimates range from about 406,000 to 532,000 GWh in 2050. These estimates are consistent with the lowest projection of about 500,000 GWh, assuming increased energy efficiency and conservation measures, given in the report, California's Energy Future: The View to 2050; however, they are less than half of the report's "business-as-usual" scenario estimate of 1,200,000 GWh for 2050, which is based on moderate economic growth and no additional energy efficiency measures (3).

The rate of growth in electricity demand depends predominantly on rates of population growth and economic growth, but is also affected by other factors, such as electrification of the transportation sector and climate change impacts on temperatures and precipitation. For example, the Energy Commission's Integrated Energy Policy Report for 2013 forecasts that electricity demand will increase to less than 285,000 GWh by 2035 because of lower population growth forecasts and higher projected energy efficiency gains than used above (4).

However, the Integrated Energy Policy Report also notes the detrimental effects that forecasted climate change impacts will have for energy. A study conducted by the Lawrence Berkeley National Laboratory (LBNL) for the 2012 California Climate Change Vulnerability and Adaptation Study (5) found that higher temperatures would decrease the capacity of thermal power plants (for example, natural gas, solar thermal, nuclear, and geothermal) to generate electricity during particularly hot periods. At higher temperatures, power plant cooling is less efficient, reducing the plant's efficiency and how much energy it can generate. California's gas-fired generating plants have a nameplate capacity of about 44,000 megawatts (MW). By the end of the century, this capacity could be reduced by as much as 10,000 MW on hot days, compared to historical maximums averaging 7,600 MW over the 1961–1990 period. The LBNL study indicates that, by the end of the century, under certain climate scenario assumptions, energy supplies would need to increase by nearly 40 percent to meet increased demand from climate change and offset the lower capacity of thermal generating plants and substations, assuming no technology advancements or population changes (4).

Projections of the state's population for 2050 reach approximately 60 million, a 30-35 percent increase over the 2012 population of about 40 million (6). Projections for the state's economic growth, measured as gross state product, range from \$3.87 to \$4.48 trillion in 2050, compared to around \$2 trillion today, or an approximate doubling of economic output (6).

Energy use will likely increase substantially due to climate change (7). Higher air temperatures are expected to increase the demand for electricity in the Central Valley and southern California, especially during hotter summer months, while reducing energy production and transmission efficiency and increasing the risk of outages. Population increases also are predicted to occur disproportionally in the Central Valley where the need for air conditioning is much greater than along coastal areas where population increases have been concentrated historically. Higher temperatures also decrease the efficiency of fossil fuel-burning power plants and energy transmission lines, requiring either increased production or improvements in the efficiency of power generation and transmission.

Extreme heat events also could cause significant impacts to the energy sector. California has a 17 percent probability of facing electricity deficits during high temperature (top 10 percent of historic temperatures) summer electricity demand periods, assuming constant technology and population growth (7). Addition of more generating units would be needed to accommodate this peak demand (8).

Potential long term shifts in precipitation patterns would significantly affect hydropower which accounts for 12 to 20 percent of the state's current electricity supply (7). Climate projections used in the 2008 California Climate Impacts Assessment resulted in only one simulation producing slightly wetter conditions by 2050, and none did so for the end of the century. A warmer and drier future climate would reduce hydroelectric generation by about 20 percent, whereas a wetter future climate would increase hydroelectric generation by 5 percent. Pacific Gas and Electric Company

(PG&E) and the Sacramento Municipal Utility District (SMUD) among many smaller utilities, receive significant portions of their annual generation from hydropower; SMUD is particularly vulnerable with hydropower accounting for up to 50 percent.

Current energy infrastructure must be adapted to address the effects of climate change, changes in electricity generation source mix and other legislative mandates, such as portfolio standards and prohibitions on once-through cooling, and growth in energy demand. This infrastructure includes natural gas pipelines, natural gas storage reservoirs, power plants, transmission lines, distribution wires and control systems. Transportation fuel infrastructure includes pipelines, refineries, and distribution systems. Infrastructure planning likely also will have to accommodate the effects of sea level rise, which is projected to be over one meter within the next century, and extreme weather events.

Most of California's electricity generation in 2010 was provided by a combination of in-state natural gas power plants and imported power, predominantly from large coal-fired plants. However, legislative mandates will significantly change the generation source mix for much of California's power over the next few decades (9).

The Renewable Portfolio Standard (RPS) program requires investor-owned utilities, electric service providers, and community choice aggregators to increase procurement from eligible renewable energy resources to 33 percent of total procurement by 2020 (10). In 2010, renewable generation represented about 16 percent (10,000 MW installed capacity) of retail sales of electricity in the state (9). If existing facilities remain operational and new facilities projects in the pipeline are completed, the Commission predicts the 33 percent target could be met by 2020; however, if historical contract failure rates of about 30-40 percent pertain, the target would be missed (9).

The Clean Energy Jobs Plan (11) supports the RPS by requiring 20,000 MW of new renewable capacity by 2020, of which 8,000 MW may be large geothermal, solar or wind projects and 12,000 MW of distributed generation, local to consumer loads. Of the current renewable portfolio, about 30 percent (3,000 MW) is distributed generation, with about 6,000 MW additional under development or authorized.

Water use reduction policy, emissions performance standards, and tightening of air quality standards are putting pressure on California's power from fossil fuel generation. By 2020, California could see retirement, replacement, or divestiture of more than 15,000 MW of fossil generation, including 13,000 MW of gas-fired generation and 2,000 MW of coal-fired generation (9). More than 13,000 MW of existing gas-fired generation will be out of compliance in 2020 with a policy to reduce once-through cooling for power generation. Plant owners indicate that long term power purchase agreements are necessary for them to repower or retrofit existing plants with alternative cooling technologies. More than 2,000 MW of coal-fired generating capacity will be divested between now and 2019 as a result of Senate Bill 1368 (Perata, Chapter 598, Statutes of 2006) which requires setting a GHG emission performance standard for baseload generation. These standards apply to new or renewed long-term contracts to purchase electricity from baseload facilities owned by, or under long-term contract to, publicly or investor-owned utilities. Currently, the standard is 1,100 lbs (500 metric tons) of CO2 per megawatt-hour (MWh), set by the California Public Utilities Commission (CPUC) and the California Energy Commission. The divestiture is predicted to reduce the share of California's electricity coming from coal-fired generation to less than 4 percent. All remaining coal contracts are expected to expire between 2027 and 2030. In addition, federal air quality constraints are resulting in closure of coal-generating plants throughout the country, including some that export power to California. Stricter regional air quality standards also are inhibiting development of new fossil fuel power plants within the state, particularly in southern California.

Nuclear power generation is constrained by a state law that prohibits building of new plants until there is a federal nuclear fuel waste repository. In mid-2012 California had just one operational nuclear power plant, the Diablo Canyon facility near San Luis Obispo. This 2.1 GW plant has an operational license until 2024. The 2 GW San Onofre facility situated between Los Angeles and San Diego, went offline in January 2012 for repairs, and in June 2013, as announced by Southern California Edison, that it would not be re-opened. Where the replacement will come from is unclear, but natural gas generation is likely for the immediate future. .

Limited availability of emissions offsets also may constrain development of new fossil fuel generation capacity. Assembly Bill 1318 (Pérez, Chapter 285, Statutes of 2009), requires California agencies to assess the need for emission offsets and new power plant capacity in the South Coast Air Basin and to examine whether rule changes and other permitting mechanisms would allow power plants to be developed while safeguarding air quality.

3. Carbon Emissions by Sector

Unlike the United States as a whole and many nations, California has laws requiring GHG emissions reductions in line with those recommended by the IPCC. In 2005, an executive order by Governor Schwarzenegger required California to reduce its GHG emissions to 2000 levels by 2010, to 1990 levels by 2020, and to 80 percent below 1990 by 2050 (Executive Order S-3-05). The passage of Assembly Bill 32 set the state on the path to meet the 2020 goal (Nuñez, Chapter 488, Statutes of 2006). Assembly Bill 32 requires a scoping plan that describes the approach California will take to reduce GHG to achieve the goal of reducing emissions to 1990 levels by 2020. The first Scoping Plan was approved by the California Air Resources Board (ARB) in 2008 and must be updated every five years to evaluate the mix of AB 32 policies to ensure that California is on track to achieve the 2020 GHG reduction goal.

The total GHG emissions in California are currently about 500 Mt CO2e/year. By 2050, GHG emission must be reduced to 77 Mt CO2/year, or from the current 13 tons/person down to 2 tons/person, accounting for population growth (12).

From 2000-2009, California's transportation sector has contributed nearly 40 percent of greenhouse gas emissions (12). The second largest sector is electricity generation, at slightly over 20 percent, with approximately equal portions of emissions from in-state and imported power generation (Figure 1). Within the industrial sector, cement plants and refineries are the largest emitters.

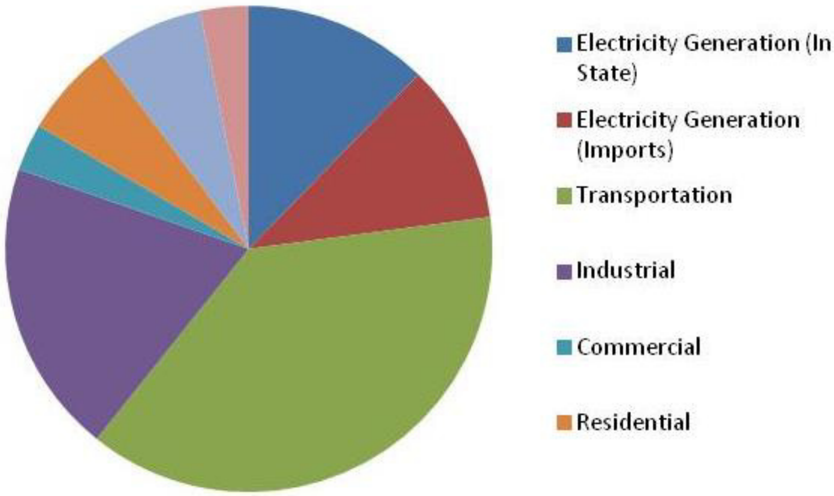

Figure 1: Greenhouse Gas Emissions for California by Sector for 2009 (12).

Overall, California's GHG emissions differ from other U.S. states and most countries in that it relies less on coal than on natural gas to meet its electricity needs and the transportation sector accounts for a much higher portion of its total emissions. Forecasts of future emissions have been done. For a business-as-usual case, assuming moderate (1 percent) economic growth, projected total GHG emissions could exceed 800 Mt (Figure 2). For the electricity sector, demand in 2050 could result in emissions of 120 Mt CO_2 per year, based on a business-as-usual scenario (Table 1).

To address emissions in the transportation sector, Executive Order S-01-07 directed ARB to create a low-carbon fuel standard (LCFS). The Order calls for a reduction of at least 10 percent in the carbon intensity of California's transportation fuels by 2020. The LCFS is separate from the mandatory reporting regulation and the cap-and-trade program and has its own reporting tools and credit-trading requirements. The LCFS framework is based on the premise that each fuel has a "life-cycle" GHG emission value that is then compared to a standard. The life-cycle analysis includes the direct emissions associated with producing, transporting, and using the fuels in motor vehicles, as well as additional emissions, direct and indirect, derived from effects of using that fuel—for example, emissions that result from changes in land use for crop-based fuels.

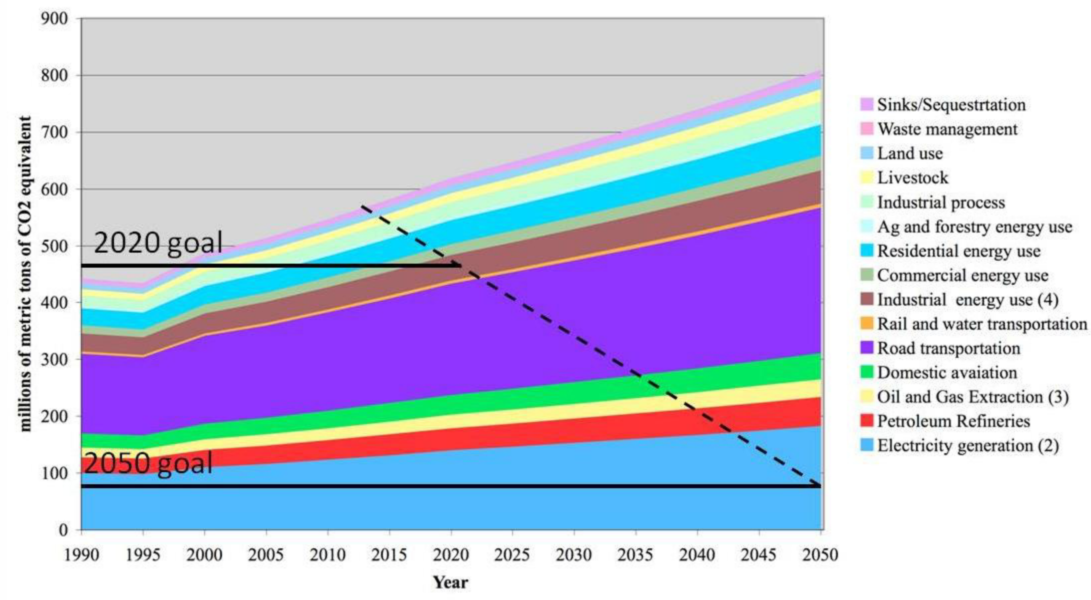

Figure 2: Forecast California GHG Emissions by Sector. Modified from Schiller (13).

Table 1: Electricity Demand and CO_2 Emissions in 2010 and Forecasts for 2050 (3).

	Demand (Twh/Year)	Emissions (Mt CO_2)
2010	300	100
2050 Goals	-	77
2050 Bas	1200	140
2050 Scenario*	500-600	60

The standards are expressed as the carbon intensity of gasoline and diesel fuel and their alternatives in terms of grams of CO_2 equivalent per megajoule (g CO_2e/MJ). Providers of transportation fuels must demonstrate that the mix of fuels they supply meet the LCFS intensity standards for each annual compliance period by reporting all fuels and tracking the fuels' carbon intensity through a system of credits and deficits. Credits are generated from fuels with lower carbon intensity than the standard. Deficits result from the use of fuels with higher carbon intensity than the standard. A regulated party meets its compliance obligation by ensuring that the amount of credits it earns (or acquires) is equal to or greater than the deficits it has incurred. Credits may be banked and traded within the LCFS market to meet obligations. The majority of California's energy use is in the electricity and transportation sectors, and these sectors also account for the majority of California's carbon emissions. As the transportation sector shifts to low-carbon fuels and electrification, the electricity sector may account for a relatively larger fraction.

4. Role of CCUS in Achieving CO_2 Reduction Goals

The path to achieving the 2020 goal and especially the 2050 goal presents significant challenges that include massive changes in energy infrastructure and consumer behavior. In order to meet targeted reductions, state agencies are pursuing five broad approaches (14):

- Conservation: Reduction of energy through changes in consumer lifestyles and workplace environments to reduce transportation fuel use, home use of natural gas, and other measures

- Energy efficiency: Efficiency must improve by about 1.2 percent per year for the next four decades in all sectors of the economy to keep costs manageable and reduce overall infrastructure requirements for new generation.
- Renewables for electricity generation: Commercialization of solar or wind generation with energy storage. A transition to low- or zero-carbon sources of electricity generation will be required in all sectors of the economy, including the transportation, residential, commercial, industrial and agricultural sectors.
- Low-carbon biofuels: Low-carbon biofuels could contribute approximately 6 percent of 2050 goals, but the use in the transportation sector may be limited by supply of biomass
- Electrification of transportation: Increased electrification of private cars, fleets, trains and other vehicles will cause electricity to grow from 30 percent of total state energy consumption to 70 percent by 2050. Over 95 percent of electricity used for transportation must come from zero-carbon or very-low carbon sources.
- Low-, zero- or net negative electricity generation: The need to maintain grid reliability will create a high demand for low-carbon dispatchable and baseload generation. This generation might come from renewable energy with storage, nuclear energy, or fossil fuel or biomass generation with CCUS. It will be exceptionally difficult to balance the grid with only renewable or only nuclear energy. A mix of low-carbon baseload, dispatchable and peaking resources will be required.
- Terrestrial sequestration: Changes in forestry and land use practices could contribute approximately 15 percent of California's total GHG emissions savings in 2050.

In addition to these measures, California has implemented a cap-and-trade market for carbon allowances. The Assembly Bill 32 Scoping Plan identifies a cap-and-trade program as one of the strategies to reduce GHG emissions. In October 2010, ARB released draft cap-and-trade regulations and designated the standardized methods established by the Mandatory Reporting Regulation of 2007 (effective January 2009) to provide source emissions data. Under cap-and-trade, an overall limit on GHG emissions from capped sectors is established by the cap-and-trade program and facilities subject to the cap must hold permits (allowances) equivalent to their GHG emissions. For example, if an oil refinery that emits 100,000 tons of carbon has credits for 90,000 tons, it either has to go on the market and buy credits for the extra 10,000 tons or lower its emissions. If it reduces its emissions, say to 80,000, then it could sell the unused permits to someone else. Trading allows facilities to purchase or sell allowances, thereby creating a market-based value for CO_2. The cap-and-trade program held its first auction in November 2012 and its second auction in February of 2013. The settlement prices for CO2 for 2013 bids at the first and second auctions were \$10.09 and \$13.62 per allowance (per metric ton), respectively (15).

Within capped sectors, while some emissions reductions will be attained through direct regulations (e.g., LCFS, vehicle efficiency measures, and renewable portfolio and electricity standards), additional reductions are incentivized by the cap-and-trade market price placed on GHG emissions. Together, direct regulations and price incentives should lead to reduced emissions in the most cost-effective manner. If the system works as designed, the most efficient companies will be financially rewarded, polluters will pay, and greenhouse gases will be dramatically reduced.

California's cap-and-trade system is designed to work beyond its borders, including other states, Canadian provinces and even other nations. ARB is working closely with British Columbia, Ontario, Quebec and Manitoba through the Western Climate Initiative to develop harmonized cap and trade programs that will deliver cost-effective emission reductions. The Western Climate Initiative jurisdictions have formed a non-profit corporation, WCI, Inc. to provide coordinated and cost-effective administrative and technical support for its participating jurisdictions' emissions trading programs.

CCUS is relevant to both California's 2020 and 2050 GHG emissions reduction goals through application to the electricity, industrial, and transportation sectors. In California, refineries and cement plants are the largest emitters in the industrial sector. While the traditional focus of CCUS applications has been for power plants or industrial facilities, CCUS can provide a pathway to de-carbonize the transportation sector through the use of electric vehicles that utilize low-carbon power produced by CCUS-equipped power plants or use in conjunction with biofuels (3).

A principal finding from the California Council on Science and Technology (CCST) reports is that California needs CCUS to meet its GHG emissions target. The Clean Energy Future 2010 report identifies several strategies to meet the state's 2020 emission reduction goal, which includes developing at least one utility-scale carbon capture and storage facility in California by 2020 (3). However, there is only one CCUS project at this scale that is under permitting consideration in California, the Hydrogen Energy California (HECA) project.

California agencies recognize the importance of CCUS in the portfolio of technologies required to meet the state's GHG emissions reduction goals. The California Air Resources Board names CCUS in its Climate Change Scoping Plan, recommending that California should both support near-term advancement of the technology and ensure that an adequate framework is in place to provide credit for CCS projects when appropriate, adopting a resolution to establish a protocol for accounting of geologic sequestration (14). Subsequently, the Board issued a directive for including separate requirements for carbon capture and geologic sequestration performed with CO_2-enhanced oil recovery, noting that carbon injected underground for the purposes of enhanced oil recovery will not be considered to be an emissions reduction without meeting ARB's monitoring, reporting, verification, and permanence requirements (12).

Regulatory agencies and policy makers also have taken several actions over the last decade to investigate CCUS technology:

- In 2003, California became a founding member of the West Coast Regional Carbon Sequestration Partnership (WESTCARB), one of the seven regional carbon sequestration partnerships funded by the U.S. Department of Energy. WESTCARB's work includes conducting technology validation and demonstration field tests, identifying major sources of CO_2 in its region, performing engineering and economic studies of capture technologies, and determining the potential in its region for storing captured CO_2 in secure geologic formations.
- The California legislature requested a report in 2006 (Blakeslee, Chapter 471, Statutes of 2006) from the Energy Commission and the Department of Conservation that contained recommendations for facilitating adoption of CCS for industrial sources in the state.
- In 2010, CARB, the CPUC and the Energy Commission convened the California CCS Review Panel to make recommendations for removing the policy and regulatory barriers to CCUS commercialization.

The current regulations implementing Senate Bill 1368 allow for the use of CCUS to meet the EPS, but the mechanisms for determining compliance are unclear. The Energy Commission regulation states that for covered procurements that employ geologic CO_2 storage, the successfully sequestered CO_2 emissions shall not be included in the annual average CO_2 emissions. The EPS for such power plants shall be determined based on projections of net emissions over the life of the power plant. CO_2 emissions shall be considered successfully sequestered if the sequestration project includes the capture, transportation, and geologic formation injection of CO_2 emissions, complies with all applicable laws and regulations, and has an economically and technically feasible plan that will result in the permanent sequestration of CO_2 once the sequestration project is operational.

Under the LCFS, CCUS is specified as an option for producers of high carbon intensity crude oil to reduce emissions for production and transport of crude oil to less than 15 g CO2e/MJ. CCUS could also be considered when used for the production of alternative transportation fuels such as hydrogen, compressed natural gas, and electricity. For CCUS to be formally incorporated into the LCFS, a quantification methodology would be necessary.

These requirements differ from Assembly Bill 32 requirements in a few key ways. First, the EPS is based on emissions over the lifetime of the plant whereas Assembly Bill 32 is based on annual emissions, and the LCFS) considers life-cycle emissions (including indirect emissions). Second, the EPS requires an economically and technically feasible plan for permanent storage, while the Bill's accounting would need a quantification methodology for any emissions and verification of permanent storage.

Infrastructure investment decisions made in this decade may determine whether or not CCUS will be included in the portfolio of technologies used to achieve the state's 2050 GHG reduction goals. Projects can take over a decade to permit, construct and bring on-line, and many will have useful lifetimes of 40 years or more. Infrastructure choices made in the next ten years thus may strongly influence the GHG emissions reduction trajectory over the next 40 years.

Capture infrastructure is source-specific. Among the state's largest GHG point sources, there is none which produce highly concentrated CO2 streams, such as ethanol plants or natural gas processing facilities. Among the state's largest point sources in the power sector are 50 relatively new natural gas combined cycle (NGCC) power plants. Cement plants and refineries are the other major types of sources.

Some studies have suggested that application of CCUS to biomass or biofuel plants may be a valuable option for the state to achieve its 2050 emissions reduction goal (3). Only about 2 percent of the state's electricity (600 MW) is generated from 33 small biomass power plants. Approximately 196 million gallons of biofuels are produced in-state by ethanol and biodiesel facilities; the demand estimated by the California Energy Commission is approximately 1.6

billion gallons per year. California's Low Carbon Fuel Standard includes eligibility of CCS as a measure to lower the carbon intensity of fuel stocks. Emissions from these sources are considerably less individually and in aggregate than from coal and NGCC power plants or petroleum refineries, but these sources are free from cap-and-trade emission constraints and would produce net-negative emissions if outfitted with CCUS. These negative emissions could be used as offsets for fossil generation or fuels if allowed by policy. The California 2012 Bioenergy Action Plan recognizes the need to analyze and mitigate potential problems with particle air emissions that have created challenges for biomass plants, such as the Klamath Biomass Plant in southern Oregon. These and other challenges facing biofuel development, such as assumptions about the accounting benefits, have been raised (e.g., (16)).

WESTCARB has performed preliminary studies of the engineering and economics for capture retrofits and new builds of typical NGCC plants in the state. Capture or separation of CO_2 from flue gas may be applied as pre-combustion, post-combustion or via oxy-combustion where an air separation plant is used to create an oxygen stream for combustion and the exhaust gas is predominantly CO_2 and H_2O. A special case of oxy-combustion, wherein a high-temperature "rocket-engine" design is used for the turbine, is also in development in California.

For out-of-state coal generation exported to California, CCUS applications are allowed for plants to meet the Senate Bill 1368 emission performance standard. As noted above, however, the Energy Commission anticipates an essentially complete divesture of coal generation from California's electricity portfolio. Many of the coal plants that contract with California are in their final decade of service (4). Furthermore, given other pressures on coal plants, such as increasingly stringent federal air quality regulations and current projections of low prices for natural gas compared to coal in the U.S. for the next few decades, it is unclear whether power providers will choose to retrofit their existing coal plants with CCUS. However, in some instances, where power generation is owned by entities, such as Native American tribes, that also are heavily invested in coal, the choice may be made to apply CCUS if capture can be done economically relative to other options.

At present there is no CO_2 pipeline infrastructure in California to carry the large volumes of CO_2 captured from point sources to storage sites. This situation contrasts significantly with other parts of the U.S. where CO_2 is carried by pipeline from natural CO2 domes to oilfields in many regions throughout the mountain, central, and southern states. There are over 6,400 km of CO_2 pipeline in the U.S. transporting over 30 Mt of CO_2 per year to oilfields for CO_2-EOR. While California has significant numbers of oilfields that are candidates for CO_2-EOR floods, the lack of CO_2 availability at an economic price, relative to historic price trends for produced oil, has precluded the application of this EOR method in the state.

The California Geological Survey performed a study for WESTCARB to establish the state's storage resource potential (17). They screened 27 basins throughout the state and focused on 10 sedimentary basins with the greatest potential. California has almost 240 Bt of CO2 storage capacity offshore, 146-840 Bt on-shore, of which 75-300 Bt in deep saline formations with between 335-1,277 Mt in oil reservoirs and 3,035-5,179 Mt in gas fields. Further studies by the California Geological Survey have refined these estimates for some regions and for offshore. One of the challenges for making estimates is that while the formations may be quite laterally extensive, they are often truncated by faulting or other geological discontinuities that would prevent the CO_2 from accessing the full extent of the formation. These are beneficial in that they provide stratigraphic and structural traps for the CO_2, but also may be potential leakage risks if CO_2 can migrate up fault planes or other discontinuities to reach the surface or potable groundwater. However, these same types of structural and stratigraphic traps have contained oil or gas for millions of years, a testament to their long-term ability to store buoyant fluids. A 2005 study of the EOR potential in California's oilfields indicated that 6.5 bbl of miscible oil could be economically recovered (18).

5. Summary and Conclusions

The case for implementing CCUS in California ultimately will be based upon need, technical readiness, economic viability, and political and public acceptance. The initially posed questions can be only partly answered from existing data and analysis, as follows:

- In what sectors does CCUS have the most potential to assist the state in reducing its CO_2 emissions?

CCUS has potential application to the power, transportation and industrial sectors in California. Studies show that increasing electricity demand will continue, with aggressive energy efficiency measures expected to contribute only about up to about half of the GHG reductions necessary by 2050. For refineries and cement plants, there are no options other than carbon capture to address process-related emissions. Applications to transportation, including to biofuels, hold promise to create net-negative emissions to assist in offsetting emissions from sources where no technology or method exists to reduce emissions.

- Do policies to facilitate CCUS enable continued use of fossil fuels even where there may be other viable options for energy generation?

Given the substantive efforts underway to diversify California's energy portfolio away from carbon-intensive fossil fuels, it appears likely that CCUS may only be included by policy when studies have demonstrated that no other options are available to decarbonize the electricity, transportation or industrial sectors. Given that both transportation and industrial sectors are likely to decarbonize by using carbon-free electricity, these sectors become dependent on the power sector for their energy supplies. Thus, it will become even more vital to California's economy to assure the reliability and sustainability of low cost electricity supplies.

Facilitating CCUS should not be viewed as a substitute for non-fossil fuel based solutions to reducing GHG emissions in contributing economic sectors. However, our economies have developed since the Industrial Revolution on fossil fuels and are inherently designed to take advantage of the benefits that fossil fuels provide. Among these benefits are high energy density, on-demand power generation, and relatively low cost. As we have exploited fossil fuels to improve our economic well being, we have increasingly come to realize the down sides—local to global environmental consequences and, in particular, CO2 increases leading to an unprecedented and unintended global experiment in climate change. Given the difficulties of integrated large fractions of any other alternative energy sources (e.g, nuclear, renewables), CCUS provides a compromise solution that enables our economies to remain strong while eliminating one of the negative consequences of continued fossil fuel use. CCUS is not a substitute for development of CO2-free technologies, but it deserves consideration and inclusion by policymakers as a bridging technology.

- Are CCUS technologies, specifically subsurface storage elements, safe and effective over the long term?

CCUS projects worldwide and analog projects provide data which support the assertion that CO2 can be stored safely in the subsurface for sufficiently long periods of time to mitigate climate change. Furthermore, these projects have tested a number of tools, including monitoring technologies, simulations, well completion methods and well and cap rock integrity monitoring to give regulators confidence that risks are measureable and monitor-able. For California, areas of particular concern are assuring safety of groundwater resources from contamination and seismic hazards, including whether pressure buildup can induced felt-earthquakes and if the presence of stored CO2 is likely to exacerbate risks of natural seismic hazards

- How can California agencies and lawmakers assure that CCUS projects are appropriately permitted, regulated, monitored, and verified?

Regulations and statutes require some changes to accommodate permitting and regulatory oversight of CCUS projects. There is a robust and growing body of knowledge worldwide that can be drawn upon to formulate permitting and regulatory requirements that assure the safe and effective operation of CCUS projects. With the enactment of policies requiring attention to climate change impacts, agencies are now tasked with safety and effectiveness responsibilities that encompass both traditional local environmental and, now, global climate change mitigation responsibilities.

An important priority for regulation is inclusion of CCUS as an option for meeting obligations set by compliance or standard requirements. Beyond mentioning CCUS as an option, methodologies that describe how storage or utilization technologies must account for CO2 must be developed so that project developers can incorporate them into business cases. Policies that support a sustainable and predictable value for CO_2 are critical to enabling CCUS technologies.

- Can the state's industrial and energy infrastructure accommodate the changes necessary to integrate CCUS?

In general, CCUS requires less change in existing energy infrastructure than most other options for decarbonizing the power, transportation, and industrial sectors. Infrastructure requirements include capture facilities at CO_2 emission sources, pipelines, and injection and monitoring wells at storage sites. In addition, a labor force with expertise in power plant, pipeline, and well drilling engineering is necessary. Capture facilities will be paid for by power producers. It is a policy decision as to whether these costs should be passed on to consumers by investor owned utilities.

California will require substantial investment in pipeline infrastructure in order for CCUS to become widespread. Because a readily available supply of low cost CO_2 would benefit California's oil industry, that industry and federal subsidies for oil production may be sources of capital for pipeline development. California's CCUS project developers may be able to repurpose or co-utilize some existing infrastructure at California's numerous oil and natural gas fields if storage is done in conjunction with CO_2-EOR or by conversion of depleted reservoirs to storage sites. Storage in saline formations will require new infrastructure and development to assure safe and effective long term storage. California has plentiful geologic storage resource to accommodate captured emissions, according to studies by the California Geological Survey.

California's labor force includes people with the right expertise to support a CCUS industry. The state is home to many small start-up companies, universities and other research organizations developing utilization technologies, and there is sufficient venture capital to fund the most promising ones. The Energy Commission has already made some investment of public funds to support growth of this sector. More public funding, possibly through cap-and-trade or EPIC programs, would accelerate development of better more cost-effective capture and innovative utilization technologies. California lacks experience in construction of high capacity CO2 pipelines, and experts may need to be brought in from other states—over 6,400 km of pipeline carry gas from natural CO2 domes to major oilfields throughout the Rocky Mountain, central and southern states.

- If CCUS is to be relied on to reduce significant fractions of California's future emissions, at what rate should CCUS projects be coming on line, and what pathways to commercialization can accommodate this rate?

If CCUS is to be a viable option for the state to use to address GHG emissions to meet its 2050 reduction goal, a large number of projects must be initiated within the next ten years. CCUS projects are large, industrial projects that require decades to plan, finance, permit, and construct. Given that over 50 percent of CCUS projects worldwide have been halted at various points within early project phases prior to actual construction, many more projects should be in development than might actually be needed to reach the 2050 goal. Capture, injection, utilization, and storage operations must then continue for at least several more decades in order to have a measureable cumulative impact on GHG emissions reductions. The size of each project is limited by the size of the point sources, and number of point sources in the case of networks, that supply CO_2 to one or more storage sites. The number of injection wells and additional pipeline to connect a well array will depend on the injectivity and storage capacity of the formation(s); thus storage site development may continue for many years after injection operations begin.

Rates of CCUS technology adoption must be sufficient to create a declining trend in GHG emissions with the right slope to intersect 80 Mt or less total emissions by 2050. It is an oversimplification to assume that technology adoptions between 2013 and 2050 will result in a linear reduction of emissions with time, but it serves to give a first-order approximation of the size of the task. With every year of delay in implementation of GHG reduction technologies, the slope becomes steeper. If the 2020 cap on new emissions is maintained after 2020, about 10 Mt per year must still be removed every year to reach the 2050 goal. This is equivalent to removing several of California's largest point sources from the emissions inventory every year.

The most expedient way to enable CCUS from an economic and infrastructure perspective is to enable utilization of captured CO_2. The largest potential uses for CO2 are for EOR, followed by building materials as a distant second. At current oil prices, CO_2 commands about $40/tonne for EOR. The state could benefit from substantive royalty revenues and job creation through the enhanced production that might be realized by using captured CO_2 in this way. Oilfield infrastructure might shorten the lead time for CCUS projects to become operational. While enabling fossil fuel production via CO_2 storage seems ironically counterproductive, there is actually significant CO_2 storage accomplished during EOR operations, and locally produced oil is preferable for several reasons over importing oil into the state. While the need for crude oil- based transportation fuels will presumably decline to zero by 2050, it is unlikely that the need for petroleum for manufacture of plastics and other materials will be completely eliminated by biologically based feedstocks. Estimates of CO_2-EOR potential in California's oilfields suggest that there should be a large enough demand for CO_2, provided oil prices remain high in the coming decades, to accelerate CCUS commercialization. Furthermore, building material CO_2 utilization technologies under development may prove to be some of the most cost effective ways to separate CO_2 from power plant flue gas, even though end products may not support paying high prices for CO_2—it may be a more cost-effective option for emitters than capture and sales for other utilization purposes.

- In state planning for future energy infrastructure, should CCUS be included as a component? What is the risk in not doing so?

California regulatory agencies and policymakers have acknowledged the potential importance of CCUS technology to assist the state in meeting its GHG emission reduction goals. However, CCUS has not been given as high a priority as many other mitigation technologies when it comes to incentivizing adoption through policies or regulation. Without actions prior to 2015 that would incorporate CCUS into the portfolio of accepted mitigation technologies, especially actions to develop accounting and regulatory methodologies, it becomes less and less likely that enough CCUS projects will be up and running to contribute substantive emissions reductions in time to meet 2050 goals. All studies done to date of California's future energy options suggest that the 2050 goal cannot be met without CCUS; therefore the risk of missing the target is high unless CCUS is included. Inclusion of CCUS means adding it to planning of future energy infrastructure.

Admittedly, because CCUS is a composite of technologies and comes in a variety of incarnations, accommodating it in planning is a complex task. Given the complexity of future energy infrastructure and the extreme nature of its makeover over the next decades, it will be almost impossible to patch in additional technology options after long term plans are adopted. For these reasons, California will lower its GHG emissions risk by accelerating policy, regulatory and practical actions that contribute to including CCUS as a GHG emissions reduction option.

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